ISSN impresa 0717-3644
ISSN online 0718-221X

Maderas. Ciencia y tecnología 2022 (24): 21, 1-10

DOI: 10.4067/s0718-221x2022000100421

APPLICATION OF A STRAIN GAUGE TO ASSESS DRYING STRESSES IN NORMAL AND TENSION WOOD OF *Corymbia citriodora*

***José Yony Cricel Sima Sánchez*[1,♣]**

https://orcid.org/0000-0002-3371-411X

***José Tarcísio Lima*[1]**

https://orcid.org/0000-0002-3513-9198

***José Reinaldo Moreira da Silva*[1]**

https://orcid.org/0000-0002-1723-8512

***Bruno Charles Dias Soares*[1]**

http://orcid.org/0000-0002-6739-3529

ABSTRACT

The quantitative evaluation of longitudinal drying strain can provide relevant information for the processing wood and lumber industry, especially with regard to reaction wood in *Corymbia*, since little has been published. The objective of this work was to evaluate the effect of the steam conditioning and the cooling on the longitudinal drying strain (*LDS*) obtained from a strain gauge, called extensometer, in boards of both normal and tension wood of *Corymbia citriodora*. Lumbers 30 mm thick were produced and kiln dried at the initial temperature of 40°C, final temperature of 65°C and drying potential of 2,1. The *LDS* were measured before and after steam conditioning on hot and cold lumbers. It was observed that the conditioning did not reduce the *LDS*. Hot lumbers showed higher *LDS* values than the cold lumbers. The *LDS* values measured in normal, tension and opposite woods were statistically similar, indicating that the type of wood was not an influential factor in the appearance of longitudinal drying stresses. Extensometer proved to be feasible for measuring *LDS*, allowing its easy and quick quantification.

Keywords: Casehardening, drying strain, kiln drying, lumber industry, reaction wood.

INTRODUCTION

In the wood drying process there are difficulties related to the appearance of defects caused by drying stresses and unequal contractions, due to moisture gradients formed through the diffusion of water, which may be intense enough to cause deformation of the material. Collapse, checks and casehardening are directly linked to excessive stresses (Mcmillen 1958).

The drying stresses are distributed in the wood structure, and if they exceed the limit of proportionality of the fibers, the plastic deformation, known as casehardening will occur (Mcmillen 1955). In this condition,

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[1]Federal University of Lavras. Forest Sciences Department. Wood Science and Technology Laboratory. Lavras, MG, Brazil.
♣Corresponding author: jose.sanchez@estudante.ufla.br
Received: 27.10.2020 Accepted: 20.01.2022

the external zones of the wood are under compression stresses due to the low moisture values and the internal under tensile stresses with high moisture (Mcmillen 1958) and techniques like steam bath conditioning are used at the end of the drying process to relieve them (Wengert 1992, Allegretti and Ferrari 2008, Rezende *et al.* 2015).

Allegretti and Ferrari (2008), for example, with the aid of an internal drying stress sensor, indicated that conditioning reduced the levels of stresses. It is possible that small amounts of internal stresses may persist in the wood at the end of drying, not causing a negative impact. Besides that, the effectiveness of steam conditioning depends on the permeability of the wood to the passage of water vapor. *Eucalyptus* wood is known for its low permeability, which suggest that the conditioning of *Corymbia citridora* can be complex, since it is still less permeable than *Eucalyptus* (Silva *et al.* 2010).

The thermal conductivity and thermal expansion of the wood should also be considered when evaluating the conditioning effect on deformations resulting from drying stresses. Thunman and Leckner (2002), with data from Groenli (1996), estimated thermal conductivity parallel and perpendicular to fibers in dry wood, with values of 0,73 W·m-1·K and 0,52 W·m-1·K, respectively. Siau (1984) reported thermal conductivity of the wood cell wall equal to0,42 W·m-1·K. Lamberts et al. (2014) pointed out that the thermal conductivities of aluminum, steel, granite and concrete are 230 W·m-1·K, 55 W·m-1·K, 3 W·m-1·K and

1,75 W·m-1·K, respectively. Comparing the thermal conductivity values found for wood and those observed for other materials, it can be inferred that wood has low thermal conductivity. Diawanich et al. (2010) reported that drying stresses could increase and decrease at the beginning of the wood conditioning due to the thermal stress of the material, when there is the difference between internal and external temperature.

Most research on drying stresses are focused on normal wood setting aside the reaction wood, which has different properties and is often identified in wood from sloping trees. Its presence could increase the manifestation of deformations during sawmilling and drying (Badia *et al.* 2005). According to Tarmian and Perré (2009), more defects are formed during the drying due to the greater contractions occurred in the tension wood. Kretschmann (2010) suggested that timber from upright and sloping trees should not be dried together since the physical, chemical and mechanical properties of the normal wood are different from the reaction wood. However, Ruelle *et al.* (2007) stated that tension wood does not follow a defined pattern in relation to its properties. Given the above, research on the behavior of reaction wood and its influence on the wood deformation during drying should deserve attention in the investigations.

In order to indirectly estimate the drying stresses of kiln-dried wood, standard techniques are traditionally used, such as the prong test (Tiemann 1942, Simpson 1991), the Mcmillen slice test (Mcmillen 1958) and the casehardening test (CEN/TS 2010). These methods are mainly based on qualitative evaluation, depend on time and break the continuity of drying, in addition to being very invasive.

Lazarescu *et al.* (2009), among some responses found in their study, stated that the correlation between shrinkage and moisture loss is useful to predict transverse drying stress. Nevertheless, the authors do not present data regarding longitudinal drying stresses.

In the lumber industries, fast, reliable and low-cost techniques for assessing and analyzing drying stresses and their associated deformation are necessary and of fundamental importance for the quality control and classification of kiln-dried wood (Tarmian *et al.* 2009).

Non-destructive methods for measuring strains in wood have already been used, such as, for example, electric strain gauges, which determine indirectly surface deformations caused by residual stresses (Kobayashi 1987). Other techniques have been proposed, such sensors that directly measures drying stresses (Allegretti and Ferrari 2008) and the restoring force technique on half-split specimen (Jantawee *et al.* 2016, Tomad *et al.* 2018, Leelatanon *et al.* 2019).

The extensometer (*Growth Strain Gauge*) is a mechanical device capable of determining longitudinal residual strain (*LRS*) associated with growth stresses in trees (Lima *et al.* 2004, Trugilho *et al.* 2007, Carvalho *et al.* 2010). However, with the extensometer it is possible indirectly to determine longitudinal drying strain (*LDS*) in kiln-dried wood, in a similar way to the presented by Tarmian *et al.* (2009), which is an indicator to assess drying stresses.

Tarmian *et al.* (2009) analyzed longitudinal strains in tension wood and normal wood of *Populus nigra*, using the strain gauge. Their results showed that the method can be interesting for that application. According to these authors, even the conventional prong test showing that there are no transverse drying stresses, the wood may bow when re-sawn. This bow is due to longitudinal drying stresses, which makes important the evaluation of the strains related to those stresses (Tarmian *et al*. 2009). The aforementioned authors observed that tension wood presented greater longitudinal strains resulting from the drying process than normal wood, using a strain gauge.

The quantitative evaluation of longitudinal drying strain can provide relevant information for the processing wood and lumber industry, especially with regard to reaction wood in *Corymbia*, since little has been published.

Given this, the objective of this work was to evaluate the effect of steam conditioning and cooling of the post-drying lumbers on the longitudinal drying strain, measured with an extensometer, in normal and tension wood of *C. citriodora*.

MATERIAL AND METHODS

Sampling and development of drying

Six trees (three erect and three sloping) of *C. citriodora* aged 60 years were selected and felled in the experimental area of the Federal University of Lavras (UFLA), Brazil. The diameters of the trunks at 1,30 m in height, the commercial heights and the slopes of the tree in relation to the ground were initially measured. Subsequently, they were sectioned in 3 m logs. Immediately, five-centimeter-thick discs were removed from each end of each log to determine basic density according to Brazilian standard ABNT NBR 11941 (2003).

The sawmilling process was carried out in the second logs (3 m to 6 m height) of all the trees (the first 3 m long log was employed for other investigation). To this end, the same had the slabs and lumbers removed in a band saw to obtain a central block with 200mm thickness. Thereafter, the blocks were sawn for the production of tangential lumbers (Figure 1). Lumbers with 3000 mm× 200 mm×30 mm (length × width × thickness) were obtained, totalling 23 pieces of upright trees and 32 of sloping trees. Based on the eccentricity of the pith from the sloping trees, it was possible to separate the lumbers derived from the tension and opposite wood (Figure 1b).

Two lumbers from upright and sloping trees were randomly selected, and a 400 mm long piece (moisture controller sample) was removed, in which the sealer was applied on the ends to prevent rapid loss of moisture. The initial moisture content of the wood was determined according to Brazilian standard ABNT NBR 11941 (2003). Subsequently, the lumbers were properly stacked for a 2 m^3 conventional kiln drying and to humidity controlling samples were inserted in the stack, making possible to follow the drying. The drying schedule developed by Sánchez *et al.* (2017) for the same species was used, based on an initial temperature of 40°C, a final temperature of 65°C and a drying potential of 2,1. Drying was routinely monitored until the end of the process.

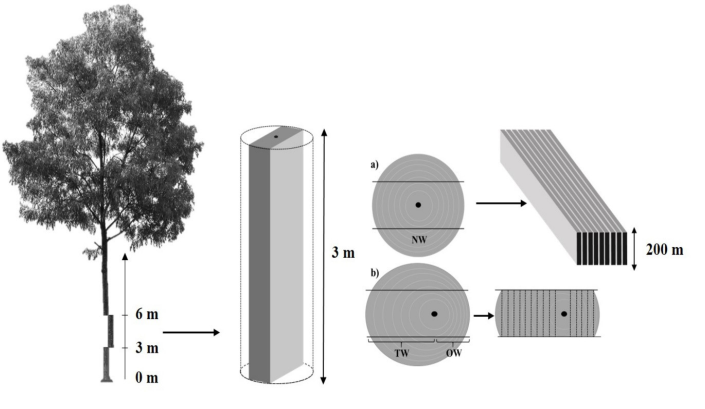

Figure 1: Scheme of the sawmilling of *Corymbia citriodora* logs. Where, (a) upright trees with central pith (NW – normal wood) and (b) sloping trees with eccentric pith (TW - tension wood and OW - opposite wood).

Assessment of longitudinal drying strain (LDS)

The longitudinal drying strain (*LDS*) (Equation 1) resulting from the longitudinal drying stresses were measured in two stages of the drying process. The first occurred after drying, when the wood load in the kiln reached the desired moisture content of 12%. The second stage was after conditioning, which consisted of steam bath for 6 h soon after drying. At each stage, the readings were measured on lumbers that came out of the oven immediately after finishing the last drying step, that is, the wood was in the condition (temperature) of 65°C and on lumbers at ambient temperature (cooled wood). For the measurements, 24 lumbers were randomly selected, taken from the kiln and cut in half (1500 mm length). Then, three regions were marked along the sawn wood (A, B and C - Figure 2), with 500 mm length for the deformation measurement, representing the repetitions of the deformation readings.

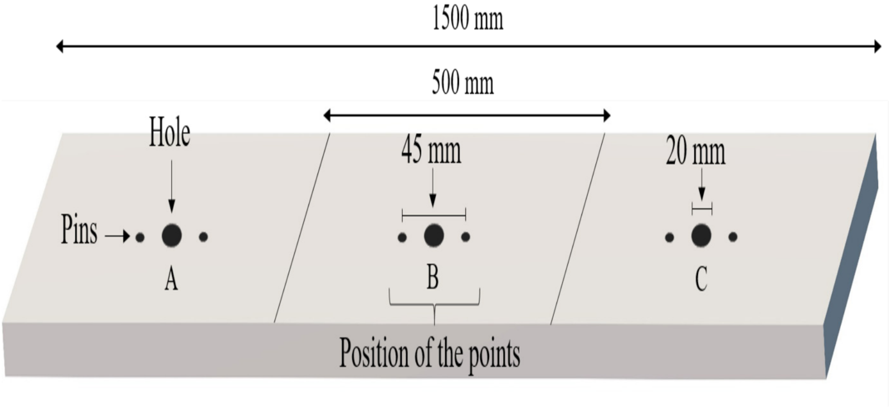

Figure 2: Positioning of the points for measuring drying strain resulting from the drying stresses (A, B and C). Where: 45 mm is distance between the two pins e 20 mm is the hole diameter

For the measurement longitudinal drying strain resulting from the drying stresses, the extensometer (*Growth Strain Gauge*) was used. In order to promote the movement of pins, 45 mm apart, the display was supported on the lumber, and a hole was carefully drilled between the pins, with a 20 mm diameter drill, measuring the deformations resulting from the release of the drying stresses. The methodology presented by Tarmian *et al.* (2009) and used in this study assumes that the hole at the depth of the lumbers thickness characterizes the mean longitudinal drying strain from the external and internal regions of the lumbers, whose resultant strain is not equals zero.

The longitudinal drying strain, as a specific deformation, was calculated according Equation 1.

$$LDS = \frac{\Delta L}{L} \qquad (1)$$

Where: *LDS*= longitudinal drying strain (specific deformation – dimensionless); ΔL = strain read in the strain gauge (linear deformation - mm); *L* = initial distance between the two pins (constant - 45 mm).

To avoid bending of the lumber during drill penetration, the deformations were measured with the pieces supported on a rigid metal base. This procedure aimed at preventing alterations of readings. Once the measurements aimed at evaluating deformations of the total stresses presented in the lumbers, the drill crossed through the plank thickness, whether they were resulting from compression or tensile stresses.

Statistical analysis

An analysis of variance (ANOVA) was made for *LDS* resulting from the drying stresses in a completely randomized design arranged in a 2 × 2 × 3 factorial design to test the equality hypothesis of the *LDS* averages found among lumbers at a temperature of 65°C and at ambient temperature; lumbers before and after steam conditioning (drying condition); lumbers derived from normal wood (upright tree), tension wood and opposite wood. The probability was 95%.

RESULTS AND DISCUSSION

The dendrometric characteristics, slope angle of trees and the basic densities of the upright and sloping trees of *Corymbia citriodora* are presented in Table 1. The average basic densities of the trees upright and sloping were similar.

Table 1: Dendrometric characteristics, slope angle and basic density of *Corymbia citriodora* trees felled at 60 years of age.

Tree	$D_{1,30\ m}$ (cm)	Commercial height (m)	Slope angle (°)	Basic density ($kg{\cdot}m^{-3}$)
Upright 1	45,19	19	0	820
Upright 2	35,49	19	0	826
Upright 3	60,79	23	0	829
Sloping 1	60,31	19	8,11	825
Sloping 2	42,65	13	8,67	830
Sloping 3	45,51	19	14,67	825

Where: D1,30 m = diameter at 1,30 m height from the ground.

Evaluation of longitudinal drying strains

Table 2 shows the ANOVA summary. With the results, it was possible to suggest that only the temperature of lumbers had a significant effect on the *LDS* at 95% probability. In addition, there was no interaction effect among factors.

Table 2: Analysis of variance of the longitudinal drying strains (*LDS*).

Source of variation	Degrees of freedom	Mean square	Calculated F
Lumber temperature (LT)	1	$8{,}42{\times}10^{-7}$	22,137*
Drying condition (DC)	1	$1{,}21{\times}10^{-9}$	$0{,}032^{ns}$
Wood type (WT)	2	$4{,}71{\times}10^{-8}$	$1{,}237^{ns}$
LT × DC	1	$2{,}76{\times}10^{-8}$	$0{,}726^{ns}$
DC × WT	2	$4{,}53{\times}10^{-8}$	$1{,}191^{ns}$
LT × WT	2	$2{,}91{\times}10^{-8}$	$0{,}764^{ns}$
LT × DC × WT	2	$5{,}19{\times}10^{-8}$	$1{,}365^{ns}$
Error	36	$3{,}81{\times}10^{-8}$	
Total corrected	47		

ns = not significant; * = significant at 95% probability.

Effect of steam conditioning of lumbers on the LDS

In Table 3 is shown the *LDS* averages as a function of the drying condition in which the wood was removed from the kiln drying, i.e., before the conditioning and after steam conditioning.

The conditioned lumbers presented *LDS* averages similar to the non-conditioned lumbers (Table 3), which may be the effect of small moisture gradients. This result differs of those found in the literature, in which it is described that, as the moisture applied by the steam bath diffuses through the outer layer to the inner layer during conditioning, the lumber gains and loses moisture. This allows the set of stresses created during drying to be relieved (Mcmillen 1958, Milić and Kolin 2008, Diawanich *et al*. 2010) and reduces possible deformations during drying (Rezende *et al.* 2015).

Table 3: Average, standard deviation and coefficient of variation of the longitudinal drying strains on non-conditioned and conditioned lumbers of *Corymbia citriodora.*

Treatment	Longitudinal drying strains		Coefficient of variation
	Average	Standard deviation	(%)
Non-conditioned	$4,21\times10^{-4}$	$2,22\times10^{-4}$	52,76
Conditioned	$4,11\times10^{-4}$	$2,51\times10^{-4}$	61,02
Calculated F	$0,032^{ns}$		

ns = not significant at 5% and 10% probability of error.

The information presented in Table 3 go beyond what has been described by Cai and Oliveira (2008), showing that the stresses can be even similar between non-conditioned and conditioned lumbers. Besides that, it may be that the results were influenced by the low permeability of *Corymbia citridora* wood (Silva *et al.* 2010), taking into account that the effect of the conditioning on the physical structure of the lumbers is null if the steam does not penetrate the wood efficiently. Pang *et al.* (2001) recommended that, for efficient conditioning, cooling is necessary so that the wood can absorb more moisture during conditioning. However, if the conditioning is not done quickly, the benefit will be small and the final effect will be an increase of moisture and not relieves of the stresses (Wengert 1992). It is possible that the residence time of the wood under the conditioning treatment was not enough to allow desirable moisture entering the wood to uniform the moisture, eliminate moisture gradients and relieve drying stresses, as described by Wengert (1992). However, the increase in temperature on the outside of the material during conditioning also slows down moisture gain (Pang *et al.* 2001). Besides that, care must be taken to avoid excessive humidification, to minimize the reversal of drying stresses, i.e., the casehardening (Kollmann and Côté 1968).

Effect of the temperature of lumbers in the longitudinal drying strains

The average values of *LDS* measured with the strain gauge for the *Corymbia citriodora* lumbers at 65°C and at room temperature are presented in Table 4.

Table 4: Average values of deformations resulting from the drying stresses in lumbers at the temperature of 65°C and ambient temperature of *Corymbia citriodora.*

Temperature	Longitudinal drying strains		Coefficient of variation
	Average	Standard deviation	(%)
65°C	$5,49\times10^{-4}$	$1,88\times10^{-4}$	34,20
Room temperature	$2,84\times10^{-4}$	$2,02\times10^{-4}$	71,00
Calculated F	22,137*		

* = significant at 5% and 10% probability of error.

According to the analysis of variance, at 5% of significance, the *LDS* average obtained in the pieces analyzed at 65°C ($5,49\times10^{-4}$) was higher than those analyzed at room temperature ($2,84\times10^{-4}$) (Table 4), showing that hot lumbers have higher internal stresses. The results also indicate that the cooling of *C. citriodora* wood up to room temperature reduces the *LDS*.

These differences are possibly due to the irregular temperature of the wood material during drying and conditioning. Temperature difference between the surface layer and the inner layer of the lumbers can increase the levels of *LDS*, due to the thermal stress of the wood (Pang *et al.* 2001, Diawanich *et al.* 2010), which, like any other substances, is expanded when subjected to high temperature and is contracted when the temperature is reduced. Furthermore, the wood has low thermal conductivity (Siau 1984, Groenli 1996, Thunman and Leckner 2002, Lambert *et al.* 2014) and because of this, it is possible that the internal region of the analyzed pieces was at a temperature lower than its external region, as confirmed by Pang *et al.* (2001). In terms of wood processing, *LDS* can be associated with the casehardening, since this phenomenon usually occurs and is measured in wood after drying in the kiln drying (Mcmillen 1958).

The thermal shock can also occur at the moment of immediate removal of the wood from the kiln drying after drying and conditioning, and may increase the *LDS* due to the temperature contact outside the kiln. Therefore, it is better wait the load of lumber to cool down gradually to avoid the stresses caused by the temperature difference between the internal and external regions of the dried wood pieces.

Effect of wood type on the longitudinal drying strains

In Table 5 is presented the average values of longitudinal drying strains obtained in normal wood lumbers derived from upright trees, and the tension and opposite woods from the sloping trees.

Table 5: Longitudinal drying strains in the different types of *Corymbia citriodora* wood.

Type of wood	Longitudinal drying strains		Coefficient of variation (%)
	Average	Standard deviation	
Normal	$4{,}45\times10^{-4}$	$2{,}40\times10^{-4}$	53,92
Opposite	$4{,}59\times10^{-4}$	$2{,}44\times10^{-4}$	53,13
Tension	$3{,}60\times10^{-4}$	$2{,}25\times10^{-4}$	62,61
Calculated F	$22{,}137^{ns}$		

ns = not significant at 5% and 10% probability of error.

The ANOVA showed no statistical difference among the *LDS* averages found in the lumbers of normal, tension and opposite wood at 5% of significance (Table 2) and this result is different than the expected. The similarity between the *LDS* for the tension wood and normal wood presented in Table 5 contradicts what was reported by Kretschmann (2010) and by Tarmian *et al.* (2009). However, the results presented in this work is understandable, based on the statement of Ruelle *et al.*(2007), that the behavior of the tension wood does not follow a defined pattern when drying.

The tension wood, in sloping *C. citriodora* trees, is affected by higher levels of growth stresses than thenormal wood of upright trees (Abreu Jr *et al.* 2017).Following this logic, it was expected that this fact would influence the *LDS*, so that the tension wood would could present higher *LDS* than normal and opposite wood. Tarmian *et al.*(2009) analyzed *Populus nigra* and stated that the *LDS* was higher in the tension wood than in the normal wood due to the presence of a higher residual growth stress in the tension wood, what did not happen in the present study.

It is feasible that the high mechanical strength, conferred by the high density of *C. citriodora* wood, will have prevented plastic deformations from the longitudinal drying stresses. Due to its high mechanical strength, the *C. citriodora* boards, even with the presence of the reaction wood, was able to dissipate that stresses without suffering permanent deformations, which is a desirable characteristic for solid wood.

CONCLUSIONS

Based on the study quantitative of longitudinal drying strains (*LDS*) for *Corymbia citriodora* wood, it was feasible to conclude that:

The *LDS* intensities were similar for conditioned and non-conditioned lumbers, indicating that the conditioning method applied was not capable of reduce these stresses.

Lumbers at 65°C presented *LDS* higher than those at room temperature, and the uneven temperature of the wood may influence this result.

The *LDS* measured in normal, tensioned and opposite wood did not present significant differences.

The analyzes presented in the present work provided information consistent with the evaluated method. The extensometer (*Growth Strain Gauge*) is able to investigate *LDS* in *C. citriodora* wood, besides has the advantages of enable quantitative data acquisition, to be a non-destructive method and has been shown an easy and fast method.

ACKNOWLEDGMENTS

The authors are grateful to Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES - Brasil), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq – Brasil) (Process 313189/2018-8) and Consejo Nacional de Ciencia y Tecnología (CONACYT – México) (Scholar ship No. 493371) for the grants and financial support during this work.

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